Simulation and Reconstruction of Charged Particle Trajectories in a Time Projection Chamber with Orthogonal Fields

RD51 Collaboration Meeting

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Outline

1. Motivation
2. Track Simulation
3. Track Reconstruction
4. Energy Reconstruction
5. Summary & Future

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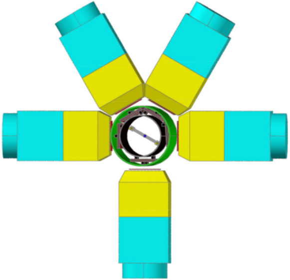
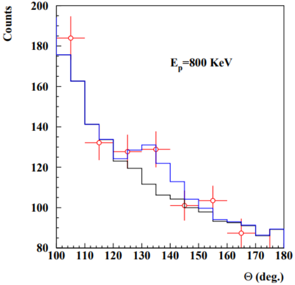
Motivation: ATOMKI Measurements

- Measurement of anomalies in the angular correlation of an electron-positron pair internally produced in excited ^{8}Be and ^{4}He

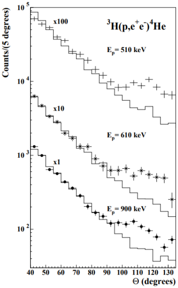


ATOMKI spectrometer. [1]

Beam pipe (black), MWPC, ΔE det. (red), *E* scintillators (yellow), light guides (blue)



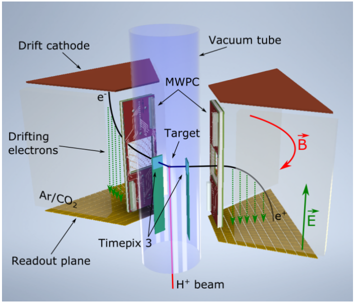
^{8}Be, e^+e^- pair angular correlation. [2]



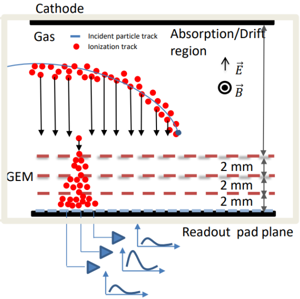
^{4}He, e^+e^- pair angular correlation. [3]

OFTPC: Detector Configuration

- Time Projection Chamber with Orthogonal Fields (OFTPC) – electric and magnetic field perpendicular (gas mixture Ar/CO_2 – 70/30)



Two out of the six OFTPC chambers. [4]



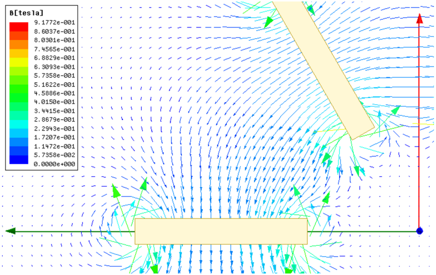
OFTPC with a triple gas electron multiplier (GEM) readout. [4]

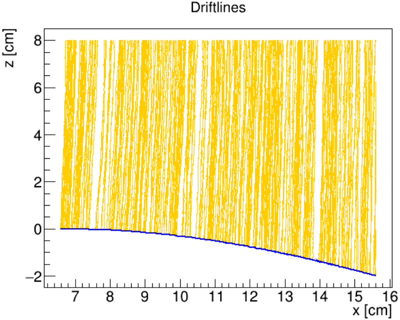
OFTPC: Reasons for Orthogonal Fields

- No solenoid – permanent magnets used to generate the field
  - Parallel fields difficult to create with permanent magnets
- Space constraints – granularity of the TPC readout limited in order to fit one SAMPA/SRS hybrid in each of the six sectors
  - Parallel fields would bend particles parallel to readout, requiring much larger number of pads
  - These trajectories would extend to more than one sector, requiring alternative architecture of the detector
- We will show a similar resolution for significantly lower cost

OFTPC: Complications

Inhomogeneous magnetic field (simulated using Maxwell [5])





- The field interferes with the direction of the drift of secondary electrons
- Curvature of the track is not constant in this field (deviation from a circle)

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Track Simulation

- Garfield++ used for track simulation
  - Primary relativistic particle simulated using the HEED program [6]
  - Secondary ionization electrons simulated using microscopic tracking (uses equations of motion)
    - Relatively slow (typically 5-30 CPU hours per track), very precise especially for small structures.
- Batches of 9702 tracks with different initial parameters simulated on a grid (MetaCentrum [7])
  - Electrons and positrons
  - 11 different energies from 3 MeV to 13 MeV (covers range for ^{8}Be)
  - 21 different angles φ and 21 different angles θ (next slide)

Track Simulation

Spherical angles (θ,φ) with respect to z
θ taken from the equatorial plane xy

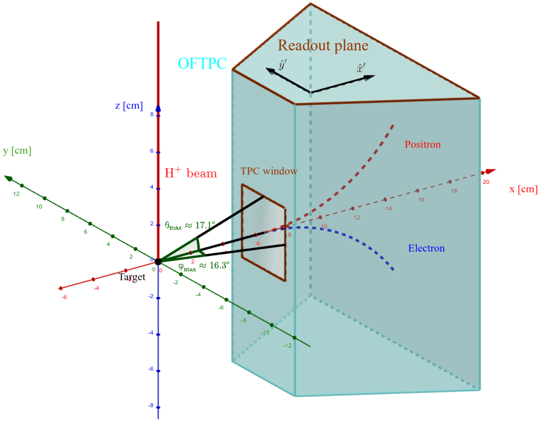
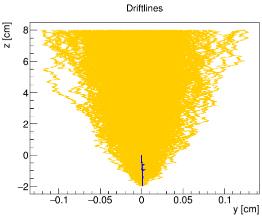


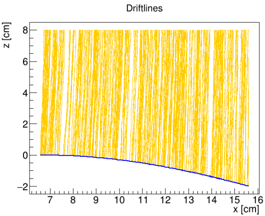
Diagram of the batch simulation parameters:
$\theta \in [-17.1°, 17.1°]$, $\varphi \in [-16.3°, 16.3°]$, $E_{\text{kin.}} \in [3, 13]$ MeV.

Simulated Track Example (microscopic tracking)

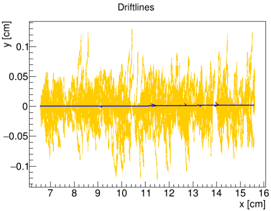
- Electron track with kinetic energy 8 MeV, $\theta = 0^\circ$ and $\varphi = 0^\circ$
- Diffusion less than 1.5 mm in both directions



Diffusion front view



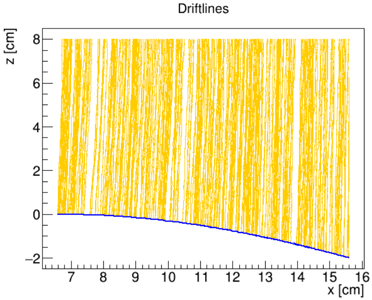
Electron drift



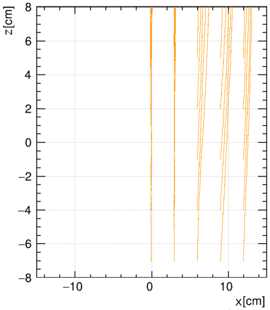
Diffusion top view

Ionization Electrons Map Simulation

- We want an unambiguous map of the drift of secondary electrons for the reconstruction
- We can use a simulation of evenly spaced electrons
  - Current spacing 5 mm, 100 electrons simulated in each location with 0.1 eV energy in a random direction



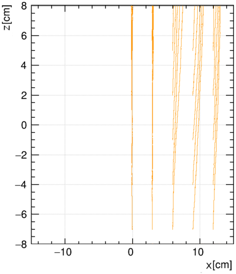
Electron drift



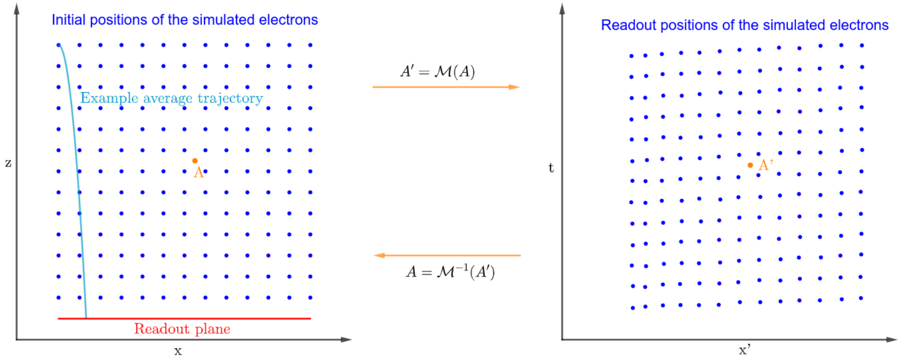
Partial simulation of the map

Ionization Electron Map Simulation

- As a result we get an approximation of a mapping from initial coordinates of the electrons (x, y, z) to the readout coordinates (x', y', t)
- By interpolating we can get the inverse map
- We can use the inverse map to finally create mapping from our discrete readout values (channel number, time) to voxels of the primary track

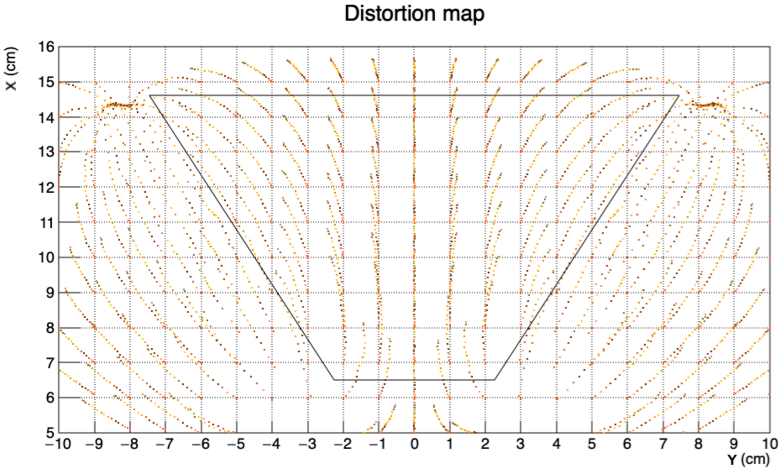


Partial simulation of the map



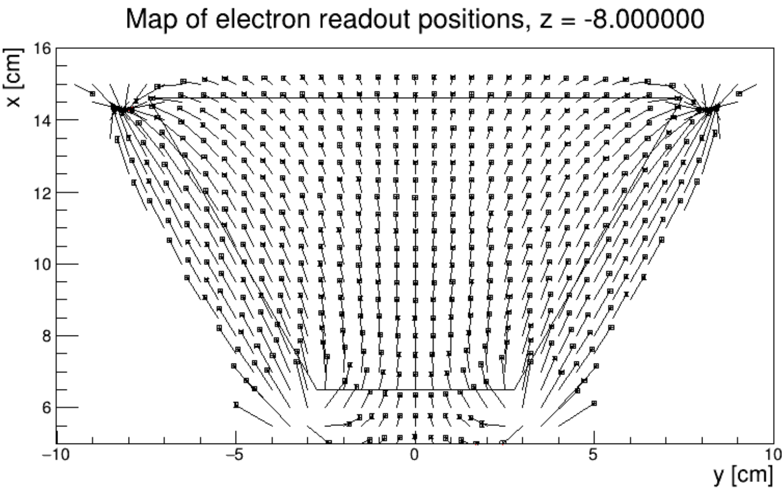
2D visualization of the simulated mapping $\mathcal{M}$ and the inverse mapping $\mathcal{M}^{-1}$.

Ionization Electron Map Simulation



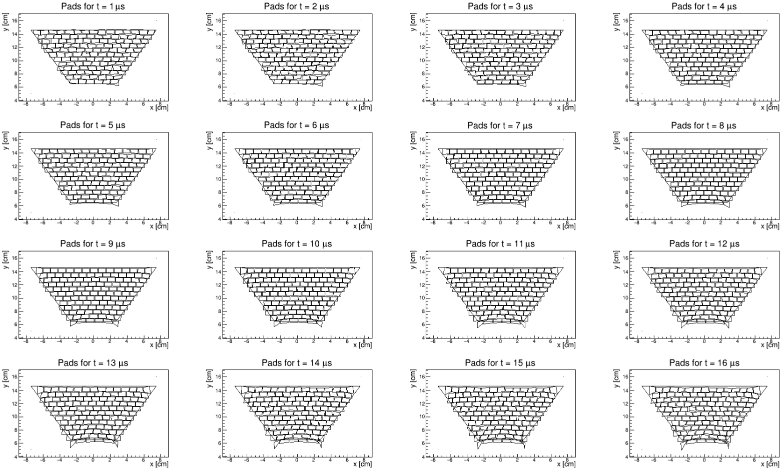
x and y coordinate distortion at different z values (denoted by colors).

Ionization Electron Map Simulation



Worst case x and y coordinate distortion for maximal initial distance from readout.

Ionization Electron Map Simulation



Pad voxel boundaries for different times.

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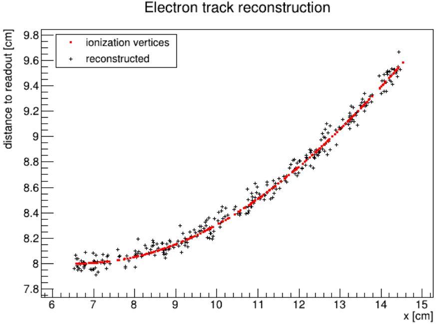
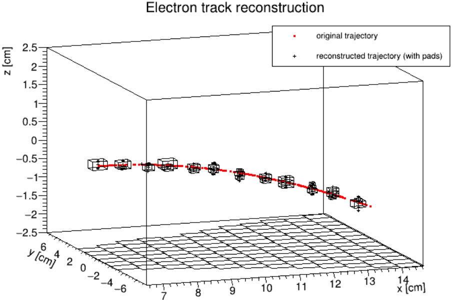
- At first using only the inverse map (not accounting for readout pads)
- Later simple reconstruction with pads and time bins, counting the number of electrons in each bin



Original and reconstructed interaction points on the simulated track



Reconstruction with pads

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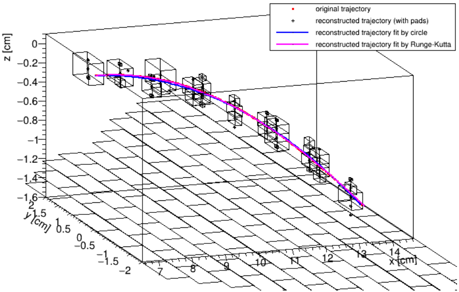
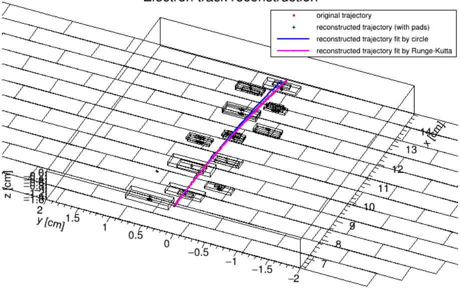
Energy Reconstruction

- Prefit with circle with smoothly attached lines
- Kinetic energy fit using 4th order Runge-Kutta
- Known initial position and direction of the particle assumed
- Currently cca 0.3 CPU seconds per track

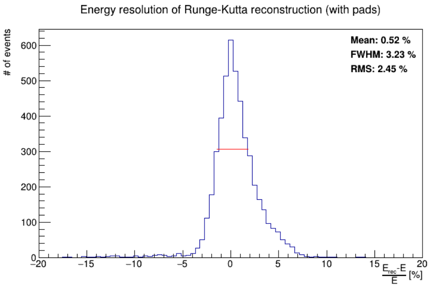




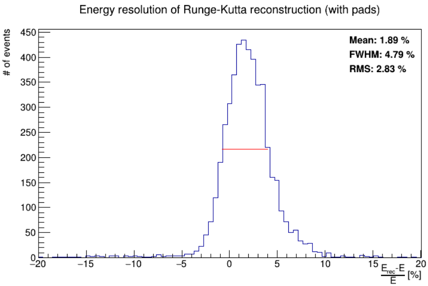
Energy reconstruction of 8 MeV electron track with both circle fit (8.36 MeV) and Runge-Kutta fit (8.072 MeV)

Energy Reconstruction Precision

Electrons



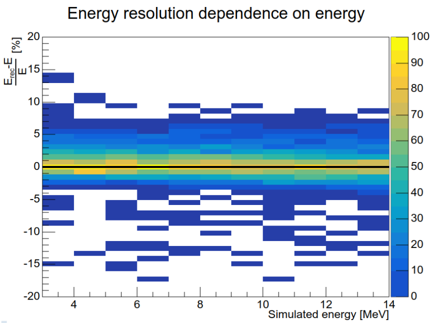
Positrons



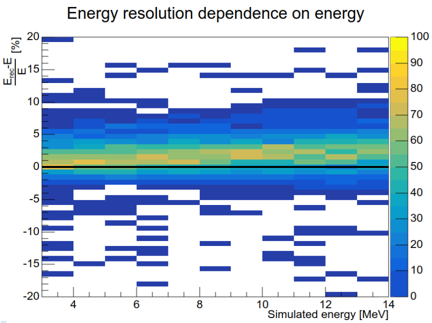
Relative reconstruction deviation of the kinetic energy of electron and positron tracks (cca 5000 of each simulated).

Energy Reconstruction Precision

Electrons



Positrons



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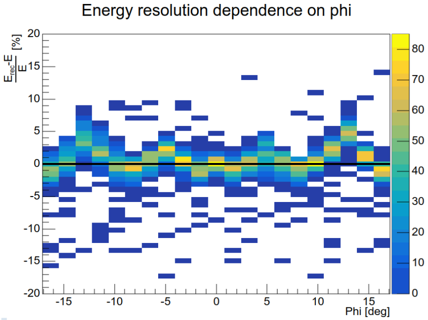
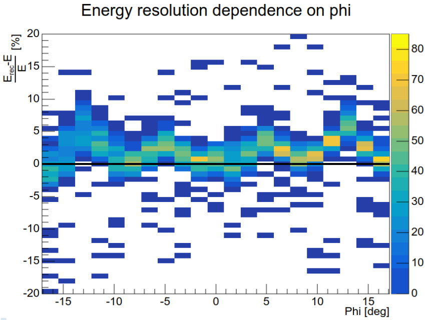


Positrons



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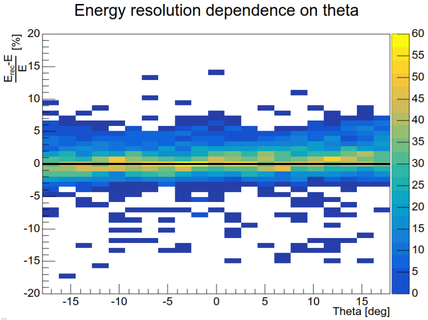
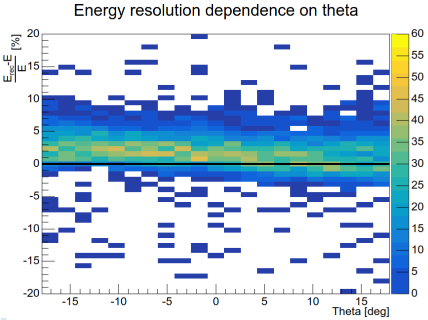
Electrons



Positrons



Relative reconstruction deviation of the kinetic energy of electron and positron tracks (cca 5000 of each simulated).

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Summary

- Several batches of tracks have been simulated for testing purposes.
  - $\theta \in [-17.1^\circ, 17.1^\circ]$, $\varphi \in [-16.3^\circ, 16.3^\circ]$, $E_k \in [3, 13]$ MeV
- The map of secondary electron positions and drift times has been generated.
- The map has been tested by the track reconstruction.
- First results suggest that:
  - Current energy resolution (FWHM) is 3.2 % for electrons and 4.8 % for positrons.
  - OFTPC works well on a simulation level.
  - Some of the systematic errors can be corrected.

Future Steps

- Account for parasitic tracks caused by high energy secondary electrons
- Account for GEM in the simulation, charge distribution between pads
- Optimize Runge-Kutta integration fit with likelihood approach (instead of least squares) if needed
- Write a faster simulation method for secondary electrons using the map
- Fix the observed systematic errors of reconstruction
- Test different geometries

Thank you for your attention.

References I

[1] J. Gulyás, T.J. Ketel, A.J. Krasznahorkay, M. Csatlós, L. Csige, Z. Gácsi, M. Hunyadi, A. Krasznahorkay, A. Vitéz, and T.G. Tornyi.
A pair spectrometer for measuring multipolarities of energetic nuclear transitions.
Nucl. Instr. Meth. A, 808:21–28, 2016.

[2] Sas, N. J. and others.
Observation of the X17 anomaly in the ^{7}Li(p,$e^{+}e^{-}$)^{8}Be direct proton-capture reaction.
arXiv, May 2022.

[3] A. J. Krasznahorkay, M. Csatlós, L. Csige, J. Gulyás, A. Krasznahorkay, B. M. Nyakó, I. Rajta, J. Timár, I. Vajda, and N. J. Sas.
New anomaly observed in $^{4}\mathrm{He}$ supports the existence of the hypothetical x17 particle.
Phys. Rev. C, 104:044003, Oct 2021.

References II

[4] A.F.V. Cortez, H. Natal da Luz, R. Sykora, B. Ali, L. Fajt.
Measurement of anomalies in angular correlation of electron and positron internally produced in excited 8Be and 4He.

[5] ANSYS, Inc.
Ansys Maxwell, Low Frequency EM Field Simulation.
https://www.ansys.com/products/electronics/ansys-maxwell.

[6] I. B. Smirnov.
Modeling of ionization produced by fast charged particles in gases.
Nucl. Instr. Meth. A, 554:474–493, 2005.

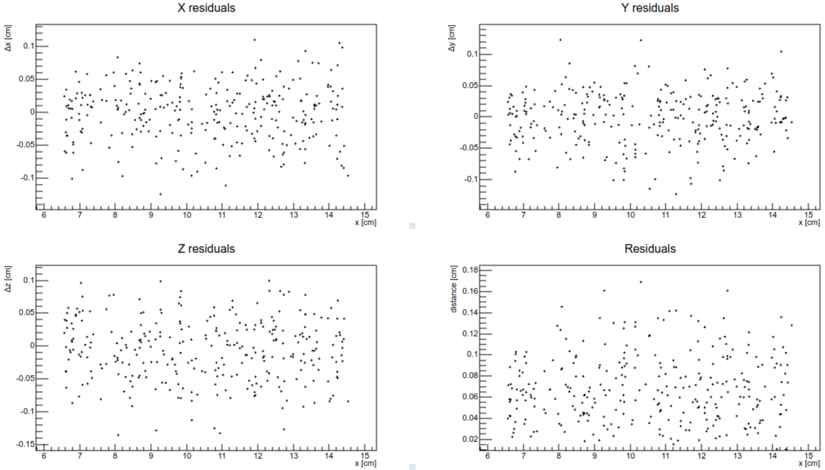
References III

[7] MetaCentrum.
Computational resources were provided by the e-INFRA CZ project (ID:90254), supported by the Ministry of Education, Youth and Sports of the Czech Republic.
https://metavo.metacentrum.cz/en.

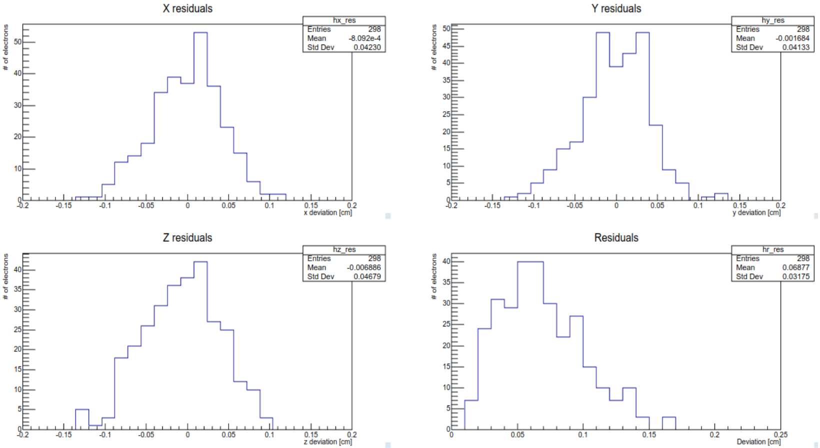
Reconstruction Testing Summary

1. Ionization electron map simulation of secondary electrons in the entire volume of the OFTPC
2. Track(s) simulated using HEED and microscopic tracking
3. Counting the number of secondaries in each pad and time bin of the readout
4. Using the map to reconstruct the position of centers of pads for given centers of time bins
5. Fitting of the reconstructed points with circle and lines fit using least squares weighted by the number of secondaries in each point
6. Using the magnetic field in the middle of the track to get first energy estimate
7. Using the 4^{th} order Runge-Kutta fit with least squares to refine the energy estimate

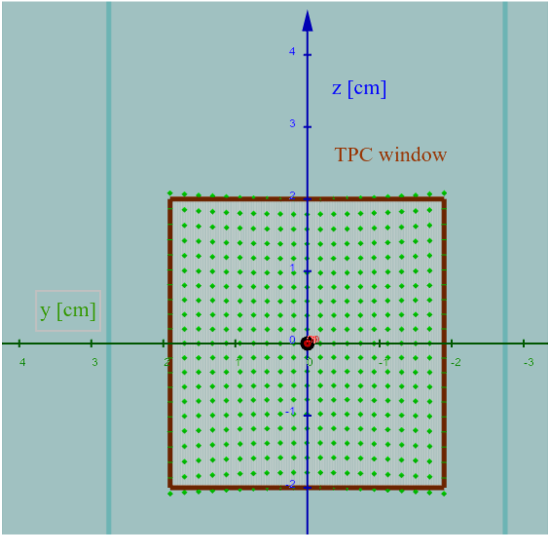
Ionization Electron Map Reconstruction Residuals



Ionization Electron Map Reconstruction Residuals



Track Simulation – TPC Window



Phi Systematic Error and Pad Geometry